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CALIBRATION OF A MACH 12 SQUARE NOZZLE

J. Ranlet
General Applied Science Laboratories, Inc.
Westbury, New York

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FOREWORD

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R. W. Brown
Captain, USAF
Gas Dynamics Division
DCS/Research

Donald R. Eastman, Jr.
DCS/Research

ABSTRACT

An experimental investigation was made of the flow field in the test section of a Mach 12 nozzle having all square cross sections. Pressure as well as temperature measurements were made in the test section of the nozzle. The results show that the Mach number within the test rhombus of the nozzle was 12.10 ± 0.20. Furthermore, the problem of focusing, which is usually encountered in axially symmetric nozzles, is eliminated.

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LIST OF SYMBOLS

M	- Mach number
P_{T_1}	- Stagnation or pebble bed pressure
P_{T_2}	- Pitot pressure (stagnation pressure behind a normal shock)
Re	- Reynolds number
T_0	- Stagnation temperature
x, y, z	- Cartesian coordinates with x as the centerline axial distance from minimum section of the square nozzle.
δ^*	- Displacement thickness

CALIBRATION OF A MACH 12 SQUARE NOZZLE

I. INTRODUCTION

In many hypersonic wind tunnel programs, expansion nozzles with large test section dimensions are required. The cost of fabricating an axisymmetric nozzle with a large test section diameter becomes prohibitive. In addition, the possibility of focusing at the axis of axisymmetric nozzles is a problem. On the other hand, the throat height of two-dimensional hypersonic nozzles becomes extremely small due to the large area ratio of high Mach number nozzles. As a result, the viscous effect in the throat region becomes extremely important.

In Reference 1, a procedure is presented for calculating the nozzle coordinates of a nozzle with a square throat and a square test section. For the case of a M = 10 nozzle, it is shown that the intermediate sections between the throat and the test section differ only slightly from a square cross section.

In an attempt to decrease the fabricating costs of hypersonic nozzles with large test section diameters, GASL constructed a Mach 12 nozzle in which every cross section was square. In this report, the results of the calibration of the square nozzle are presented. The author wishes to thank Dr. Victor Zakkay for his valuable discussions in the work reported here.

II.

NOZZLE DESIGN AND FABRICATION

A. Design

In Reference 2, the coordinates of a family of axisymmetric hypersonic nozzles are presented. The nozzle coordinates were calculated assuming a three-dimensional source flow for the initial nozzle expansion and then an axisymmetric characteristic flow field solution to obtain a uniform test section flow. The design of the square nozzle is based on the $M = 12$ nozzle design presented in Reference 2 with a half-cone angle of 8 degrees. Figure. 1 is a sketch of the axisymmetric nozzle indicating the required length to obtain uniform flow. Tabulated in Table 1 are the aforementioned axisymmetric nozzle coordinates with a boundary layer displacement thickness correction corresponding to a stagnation pressure of 1500 psi and a stagnation temperature of 2500°R.

The square nozzle design has the same axial variation of area as the axisymmetric nozzle whose coordinates are tabulated in Table 1. The coordinates of the square nozzle are tabulated in Table 2. As can be seen in Figure 1, the nozzle length required to obtain a uniform Mach number distribution throughout the entire inviscid test section diameter is approximately 235 inches. Due to the lack of funds at the time of fabrication, the nozzle was terminated at 145.6 inches. The test section was located in a region where the test rhombus diameter was of the order of 8 inches. An extension to the nozzle for the purpose of achieving a uniform Mach number distribution throughout the test section diameter has been designed.

B. Fabrication

Because of the high heat transfer rates and static pressure in the vicinity of the nozzle throat, the throat section of the nozzle was fabricated from four pieces of stainless steel bar stock. The external configuration of the throat section is a circular cylinder which fits into the retaining block of the GASL heater. Downstream of the throat section, where the static pressures and heat transfer rates are relatively low, the nozzle was fabricated from four pieces of stainless steel plate, one-half inch thick. A photograph of the nozzle is presented in Figure 2. As can be seen in this photograph, the edges of the upper and lower plates were contoured so that when they were bent and welded to the widewalls of the nozzle the required area distribution was obtained. Struts were welded on the exterior of the nozzle at several axial stations to minimize warping of the nozzle when welding. As a consequence of this fabrication technique, no internal machining of the nozzle contour was required, thereby reducing the cost and time of fabrication.

III. EXPERIMENTAL EQUIPMENT

A. Air Heater

The square nozzle calibration tests were performed with the nozzle attached to the GASL high temperature pebble bed heater as shown in Figures 3 and 4. The pebble bed heater consists of a 1500 psi pressure vessel containing a bed of alumina pebbles. The pebble bed is heated by "Globar" electrical resistance heating elements and is separated from the walls of the pressure vessel by insulating material. During a test, air from the air supply system is heated to a temperature on the order of 2000°R by passing it through the pebble bed before it enters the nozzle.

B. Air Supply and Vacuum Systems

The air supply system consists of three 50 HP compressors, separators and dryers to decrease the dew point of the air, air storage flasks with a total volume of 1000 cubic feet, and the necessary control valves for regulating the air flow into the heater. The air storage system is rated for a maximum pressure of 2000 psi.

The required pressure ratio for calibrating the square nozzle was obtained by connecting the downstream end of the diffuser to the 40 ft. diameter vacuum sphere. The sphere is evacuated to a pressure of several mm. Hg prior to a test by two Beach Russ mechanical pumps with a total pumping capacity of 1500 cfm.

C. Instrumentation

Pitot pressure measurements were made using a rake with 5 pitot pressure probes aligned with the flow direction. Pressure transducers were used to sense the pressures and their outputs were recorded on a multichannel oscillograph. The pressure transducers were calibrated prior to the test series and the linearity factor and reference level were checked prior to each test.

Test section stagnation temperatures were measured using two types of probes as shown in Figure 5. Probe 1 was constructed using 0.093" O.D. stainless steel tubing with 36 gage chromel-alumel thermocouple wire passing through the tubing. Probe 2 was constructed using 1/16" Ceramo wire (30 gage Chromel-Alumel thermocouple wire).

The instrumentation used for recording the pitot pressure and stagnation temperature data consisted of a 12 channel oscillograph and two slidewire potentiometers. The oscillograph was calibrated at regular intervals and the slide wire potentiometers were calibrated before each test to insure the accuracy of the measurements.

IV. EXPERIMENTAL RESULTS

A. Test Conditions

The calibration of the nozzle was conducted at a stagnation pressure of 1200 psia and a stagnation temperature of 2000°R. The corresponding test section Reynolds number was 1.06×10^6 per foot. A diffuser with an area contraction ratio of 0.65 was located downstream of the nozzle to increase the testing time. With an initial pressure of 15 mm Hg in the vacuum sphere, the running time of the nozzle was 8 seconds.

B. Presentation of Experimental Data

Pitot pressure profiles were measured at various Z locations at the axial station X = 123.7" (Station 1). The resulting data are presented in Figures 6 to 9, non-dimensionalized with respect to the pebble bed stagnation pressure. Also presented in these figures are the corresponding Mach number distributions determined from the aforementioned pressure ratios. In addition, pitot pressure profiles were measured at the center line of the tunnel (i.e., y=o) at two axial stations located 10.9 inches apart (i.e., x = 112.8 inches (Station 2) and x = 123.7 inches). The resulting pitot pressure profiles are shown in Figure 10. Figure 11 presents the Mach number distribution at Station 2 for any two typical tests. As can be seen from the figure, the Mach number distribution is repeatable from test to test. Stagnation temperature measurements were also made at Station 2 and the results are presented in Figure 11. The Mach number distributions at Station 1 are presented in Figure 12 in grid form.

C. Discussion of Experimental Results

From the data presented in Figures 6 to 12, it can be concluded that a region of uniform flow exists in an 8 inch square area of the nozzle at the axial station x = 123.7 inches. The Mach number in this region is equal to 12.10 ± 0.20. The center-line measurements at x = 112.8 inches and x = 123.7 inches indicate that the axial gradient of Mach number in the 10.9 inch length is

$\pm$ 0.15. From the stagnation temperature data, it appears that the stagnation temperature is also uniform in the 8 inch square test core. Surface pressure measurements on opposite sides of a 5° half angle wedge were used to obtain the flow angularity in the test core of the nozzle. The observed pressures indicated that the flow was parallel to the nozzle axis to within the accuracy of the measurements (i.e., $\pm$ 3% in surface pressure).

V. CONCLUSIONS

An experimental investigation has been conducted to determine the feasibility of utilizing square nozzles for large test facilities. It is shown that square nozzles may be fabricated at a substantial reduction in cost over that of axially symmetric nozzles. For nozzles of the size tested here, the cost is of the order of one third the price of that of a machined axially symmetric contoured nozzle. For nozzles with large test sections, the saving should even be more. Furthermore, a square test section provides easier model accessibility and schlieren window installation.

A survey of the flow field in the test section of the square nozzle indicated a slight deviation from that of the axially symmetric nozzle. The flow field within the test rhombus of the nozzle was parallel to the nozzle axis and showed a variation of $\pm$ .20 in Mach number from 12.1.

Therefore, for test sections of the order of 10 feet or larger, where a uniform flow field is desired, it appears that a square nozzle following the procedure outlined here is a practical solution.

VI.

REFERENCES

I. Beckwith, Ivan E., Ridyard, Herbert W. and Cromer, Nancy, The Aerodynamic Design of High Mach Number Nozzles Utilizing Axisymmetric Flow with Application to a Nozzle of Square Test Section, NACATN 2711, June 1952.

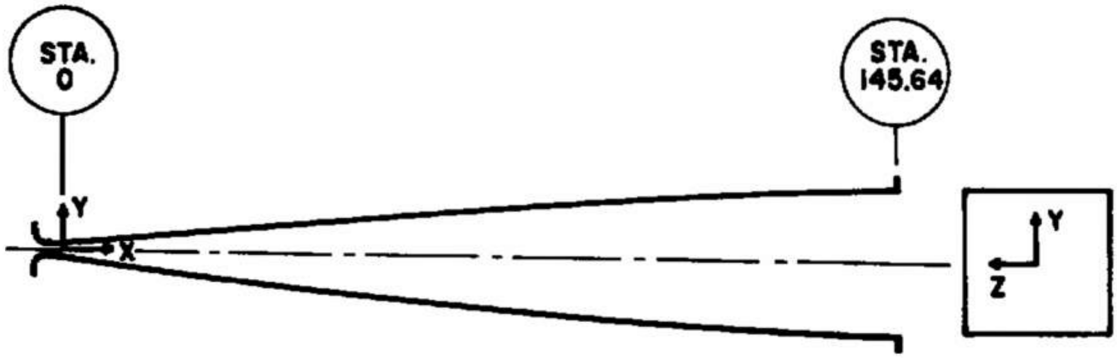
II. Cresci, Robert J., Tabulation of Coordinates for Hypersonic Axisymmetric Nozzles, Polytechnic Institute of Brooklyn, Pibal Report 463.

TABLE I

X	$Y+\delta^*$	X	$Y+\delta^*$	X	$Y+\delta^*$	X	$Y+\delta^*$
0	.366	24.468	3.975	56.370	8.152	99.457	11.887
3.00	.795	26.655	4.312	59.677	8.505	103.740	12.172
4.50	1.012	28.806	4.642	63.075	8.857	108.082	12.450
6.00	1.230	31.177	4.980	66.562	9.195	112.522	12.720
7.50	1.447	33.562	5.332	70.132	9.540	117.022	12.975
9.00	1.665	36.015	5.670	73.792	9.870	121.612	13.230
10.50	1.890	38.595	6.007	75.652	10.035	126.270	13.470
12.00	2.107	41.295	6.367	79.440	10.365	131.002	13.710
13.50	2.332	44.100	6.720	83.310	10.680	135.817	13.927
15.00	2.557	47.017	7.080	87.262	10.987	140.692	14.152
18.00	3.000	50.040	7.440	91.297	11.302	145.642	14.375
21.00	3.457	53.160	7.800	95.407	11.595		

AXISYMMETRIC NOZZLE WITH δ^* CORRECTION

TABLE II



X	±Y, ±Z	X	±Y, ±Z	X	±Y, ±Z
0.000	.323	33.562	4.725	83.310	9.465
3.000	.704	36.015	5.025	87.262	9.737
4.500	.896	38.595	5.323	91.297	10.016
6.000	1.090	41.295	5.642	95.407	10.276
7.500	1.282	44.100	5.955	99.457	10.534
9.000	1.475	47.017	6.274	103.740	10.787
10.500	1.675	50.040	6.593	108.082	11.033
12.000	1.867	53.160	6.912	112.522	11.273
13.500	2.066	56.370	7.224	117.022	11.499
15.000	2.266	59.677	7.537	121.612	11.725
18.000	2.658	63.075	7.849	126.270	11.937
21.000	3.063	66.562	8.149	131.000	12.150
24.468	3.522	70.132	8.454	135.817	12.342
26.655	3.821	73.792	8.747	140.692	12.542
28.806	4.114	75.652	8.893	145.642	12.739
31.178	4.413	79.440	9.186		

MACH 12 SQUARE NOZZLE COORDINATES

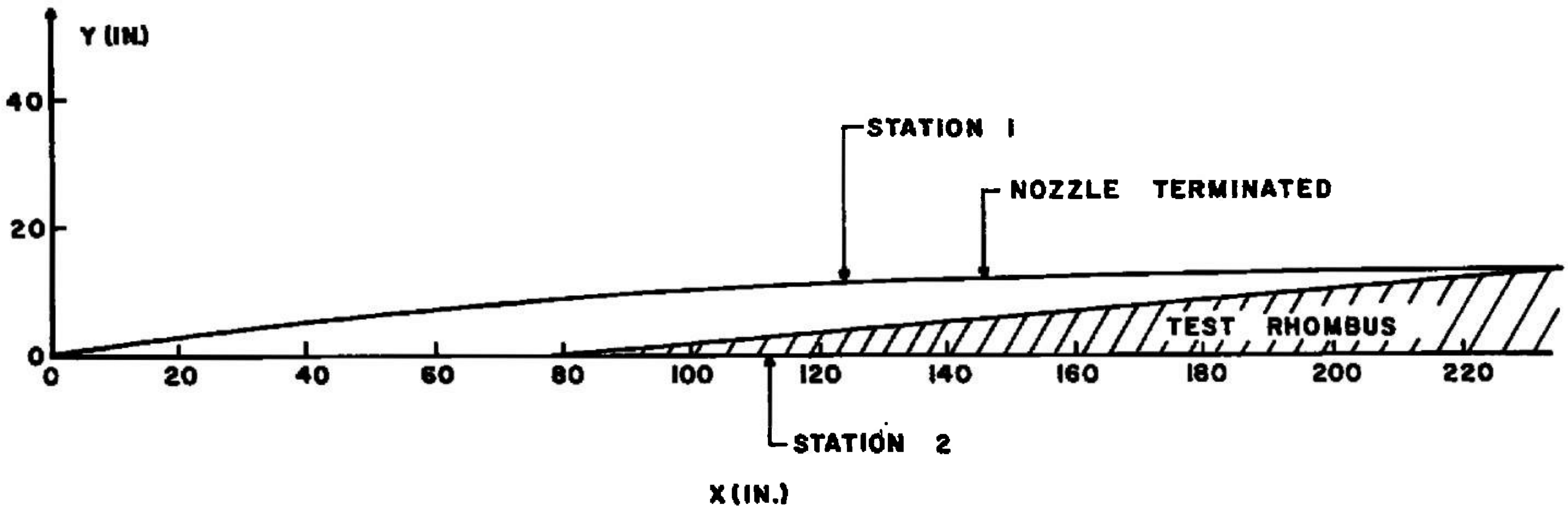


Fig. 1 Inviscid Axisymmetric Nozzle Coordinates

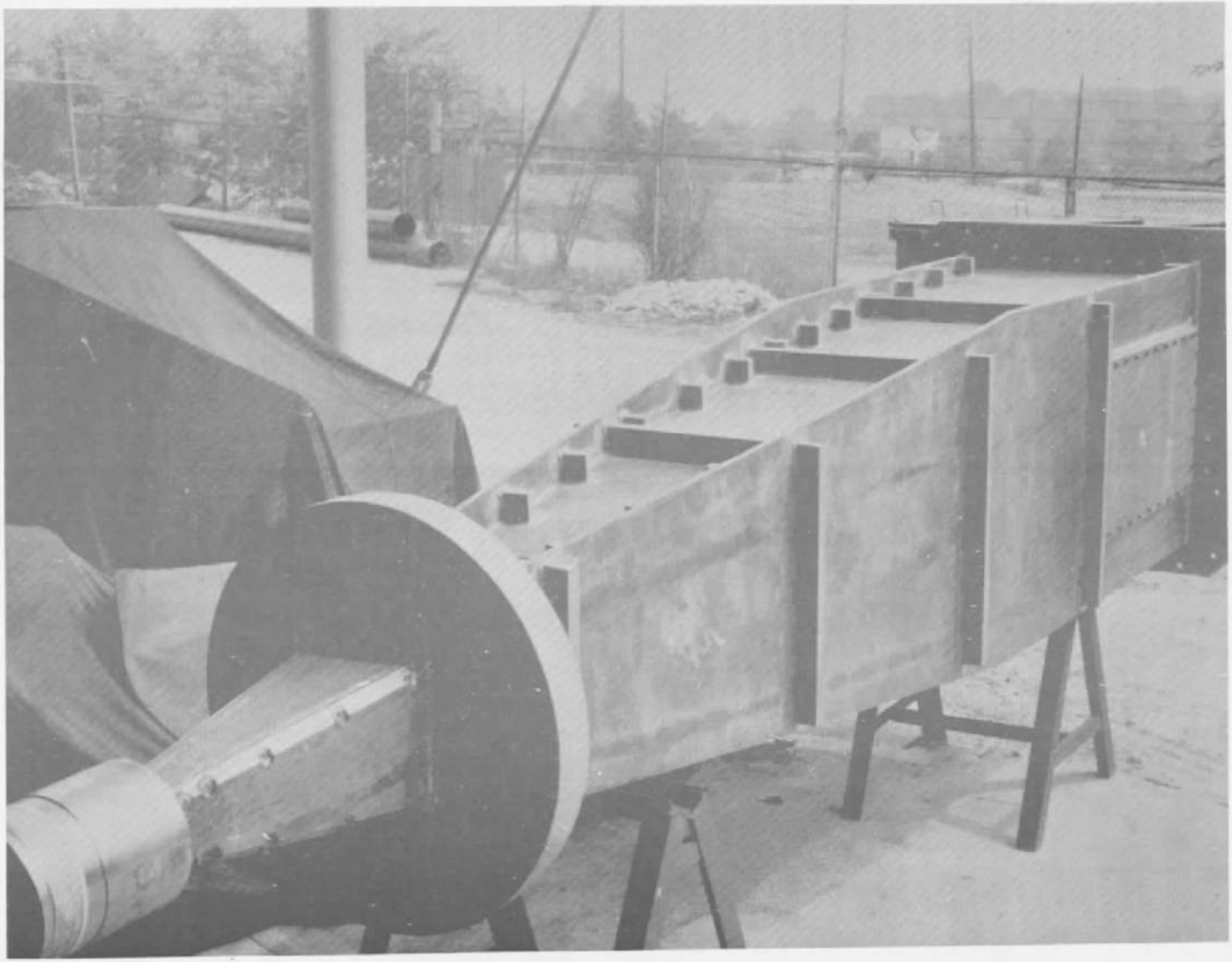


Fig. 2 Photograph of Square Nozzle

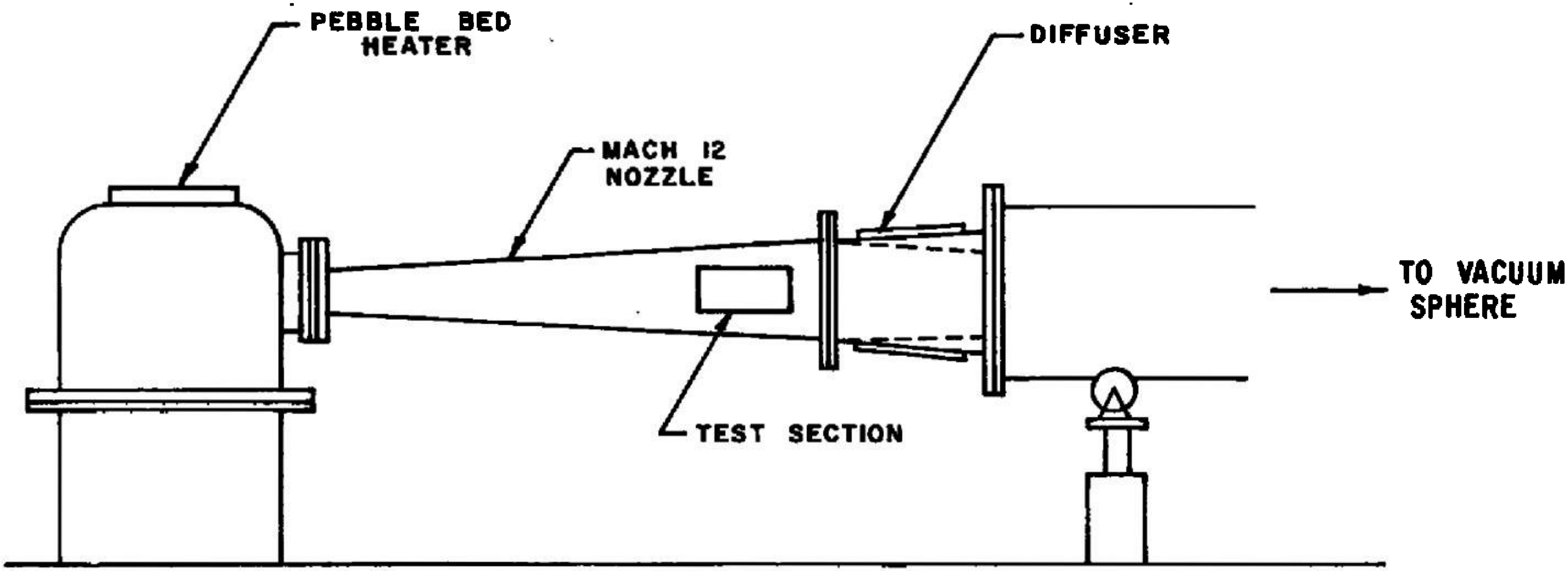


Fig. 3 Schematic of Mach 12 Square Nozzle Installation

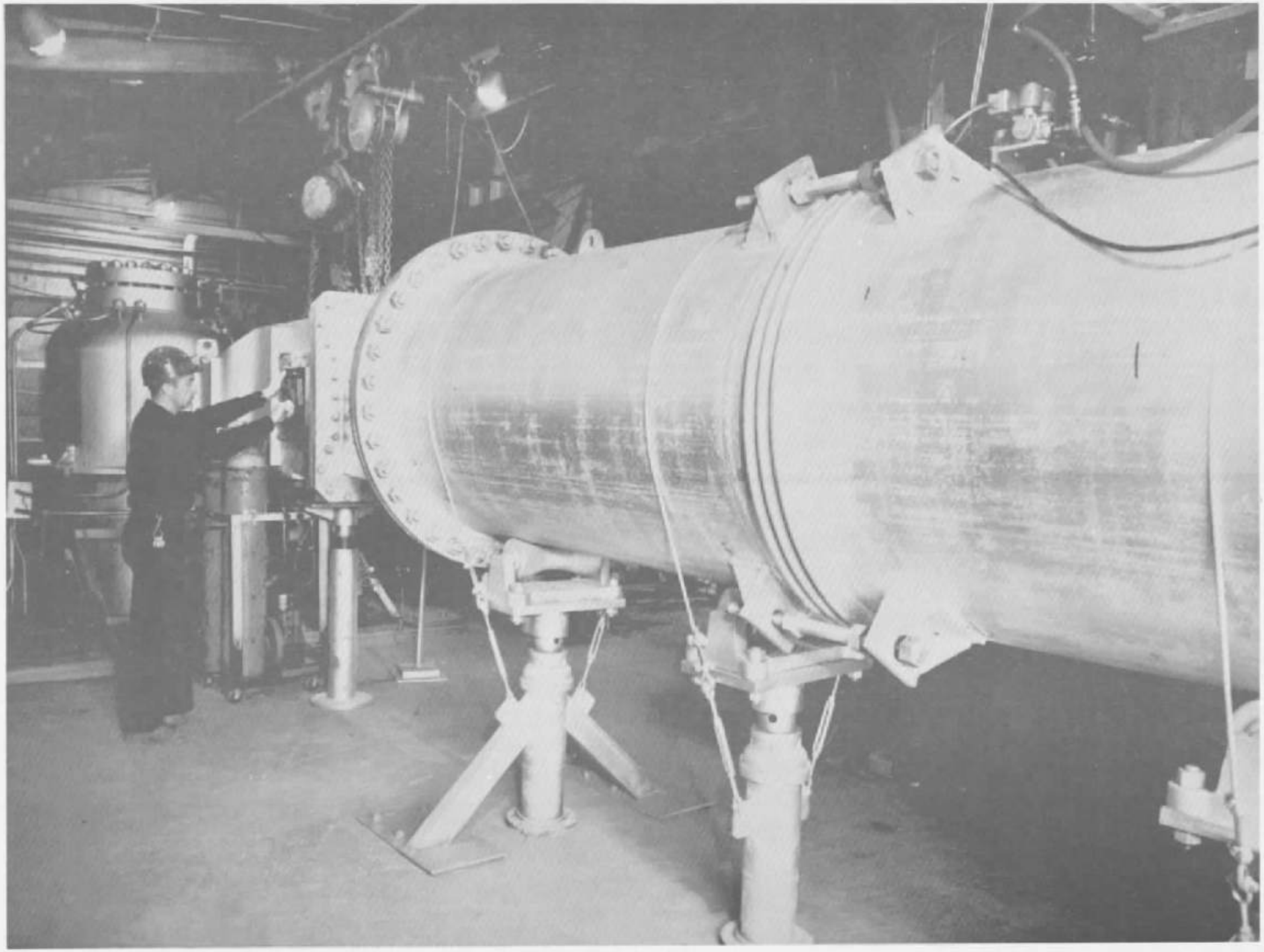
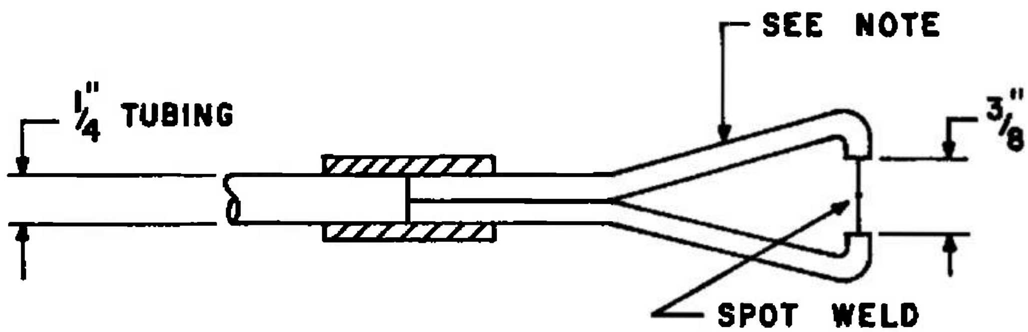


Fig. 4 Photograph of Mach 12 Installation



NOTE : PROBE 1 - .093" O.D. STAINLESS STEEL TUBING WITH 36 GAGE C/A THERMOCOUPLE WIRE.

PROBE 2 1/16" CERAMO WIRE (30 GAGE C/A WIRE)

Fig. 5 Stagnation Temperature Probes

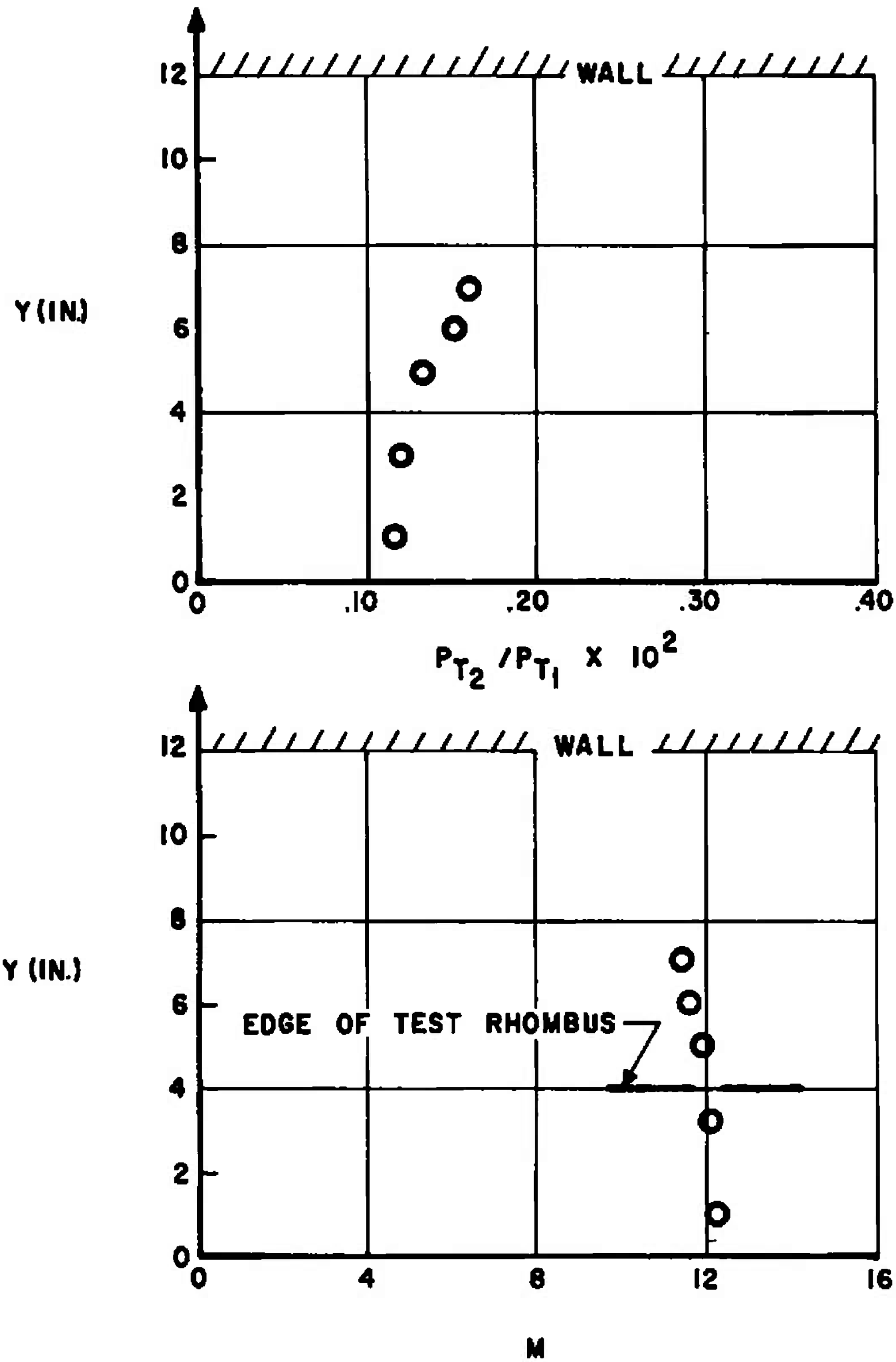


Fig. 6 P_{T_2}/P_{T_1} and M vs. Y for Z = 0 at X = 123.70"

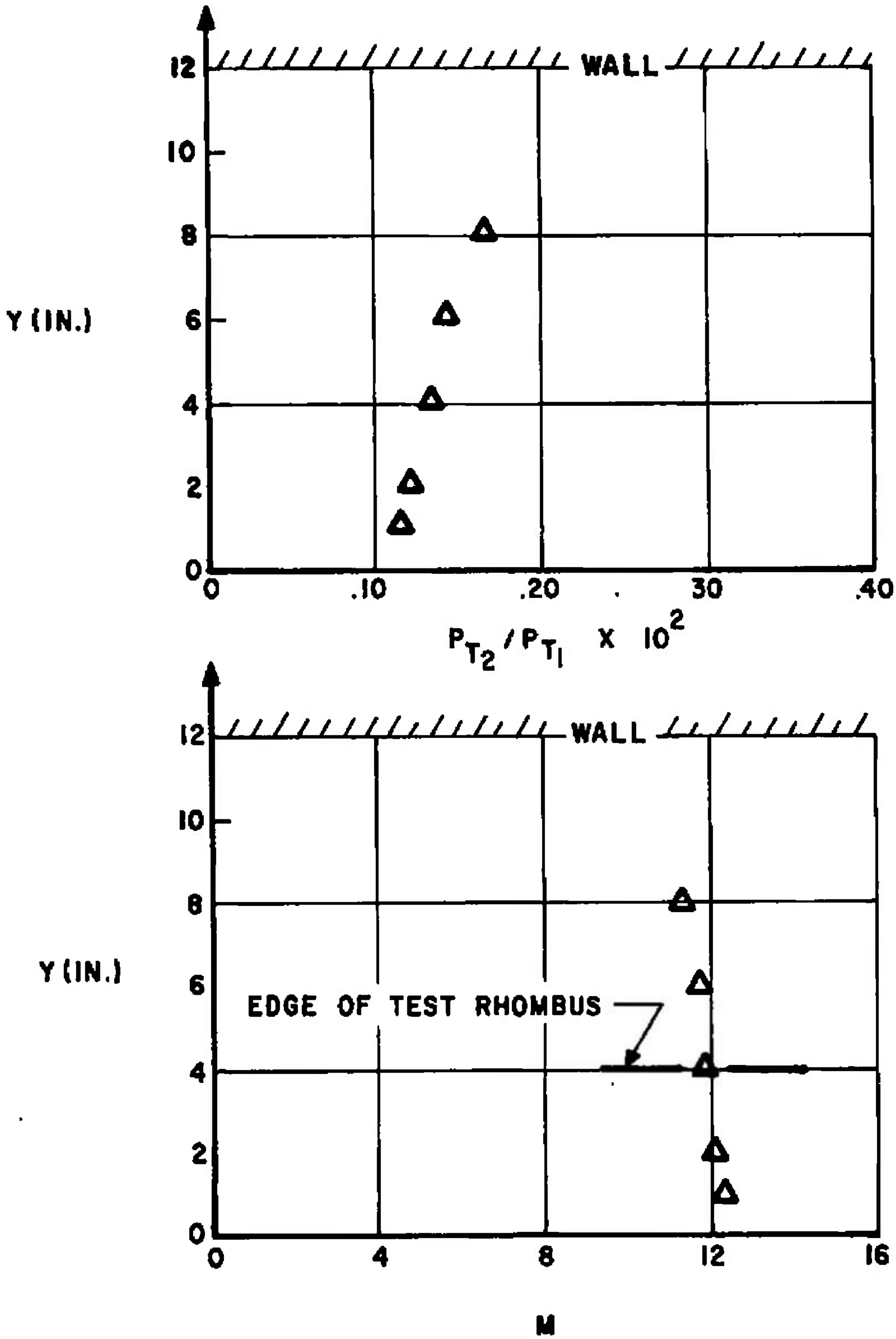


Fig. 7 P_{T_2}/P_{T_1} and M vs. 6 for Z = 4" at X = 123.70"

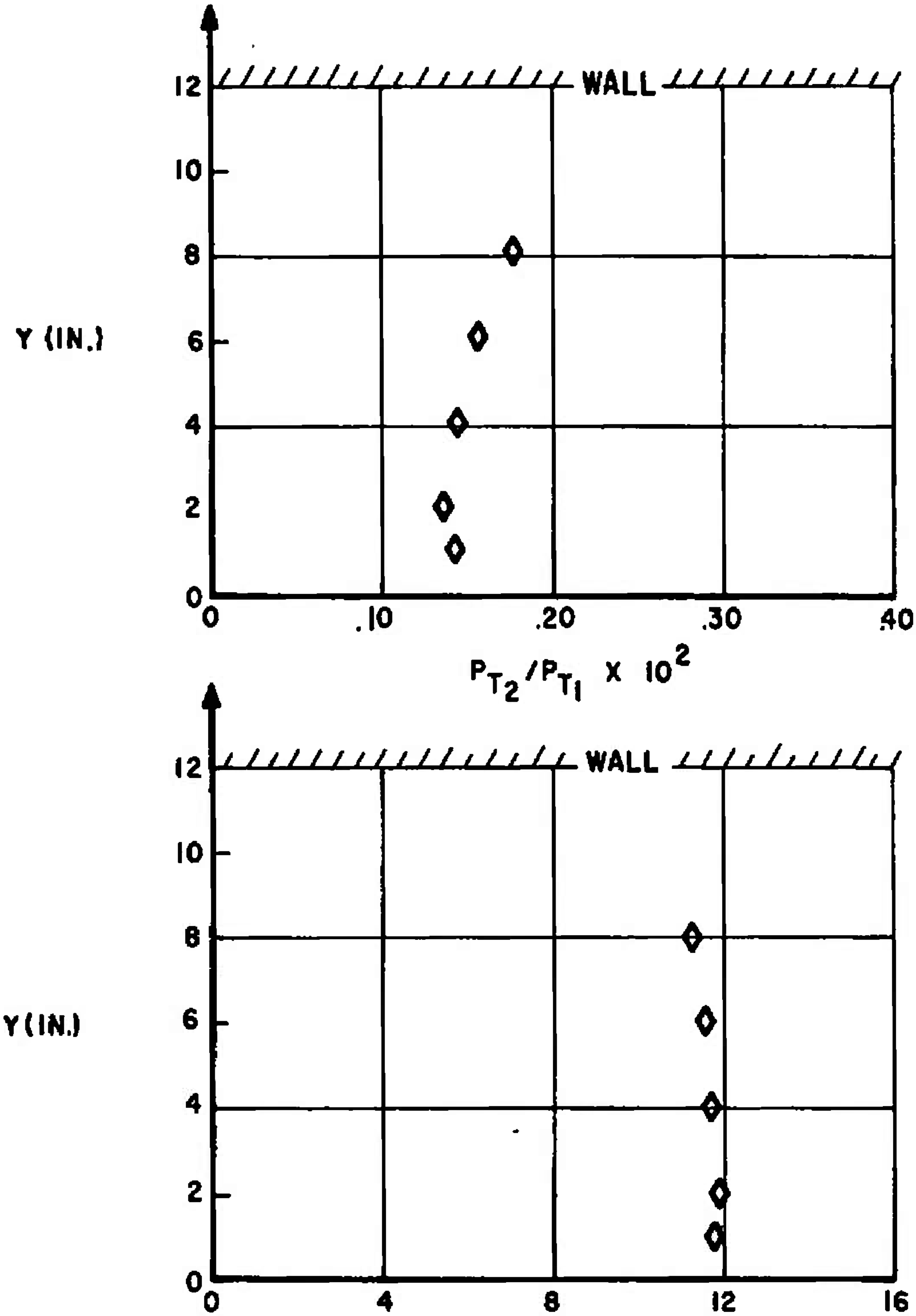


Fig. 8 P_{T_2}/P_{T_1} and M vs. Y for Z = 6" at X = 123.7"

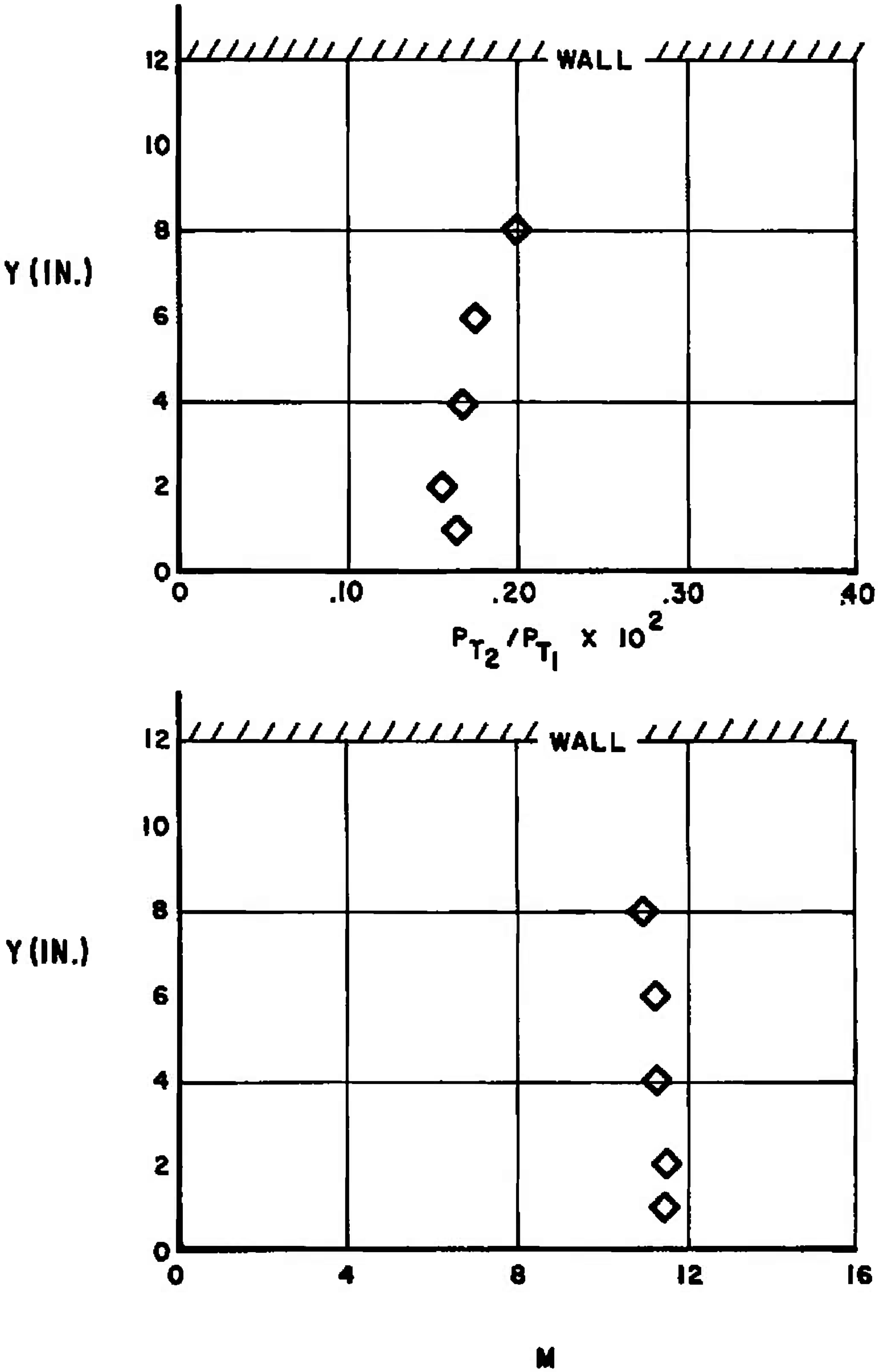


Fig. 9 P_{T_2} and M vs. Y for Z = 8" at X = 123.7"

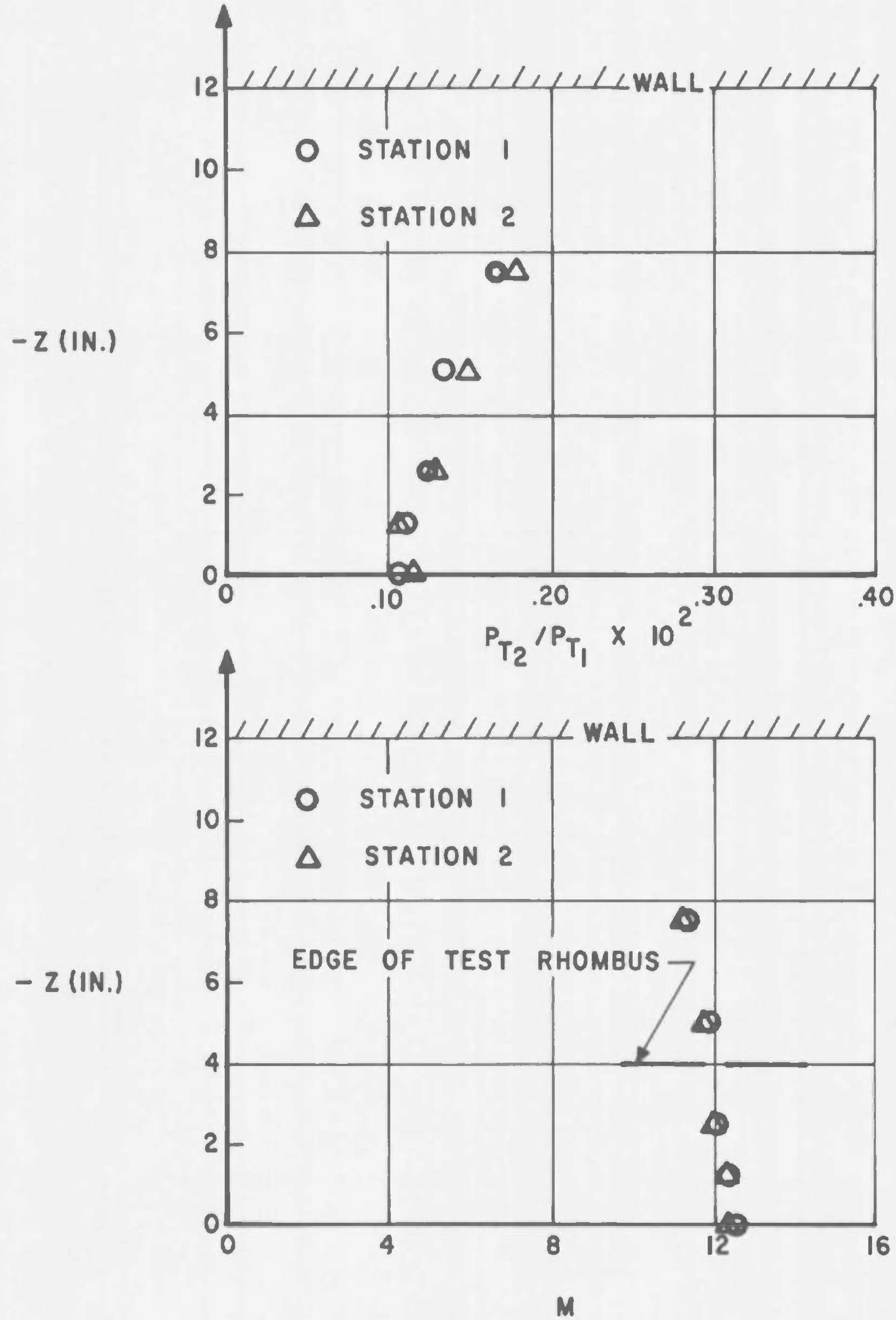


Fig. 10 P_{T_2}/P_{T_1} and M vs. Z for Y = 0

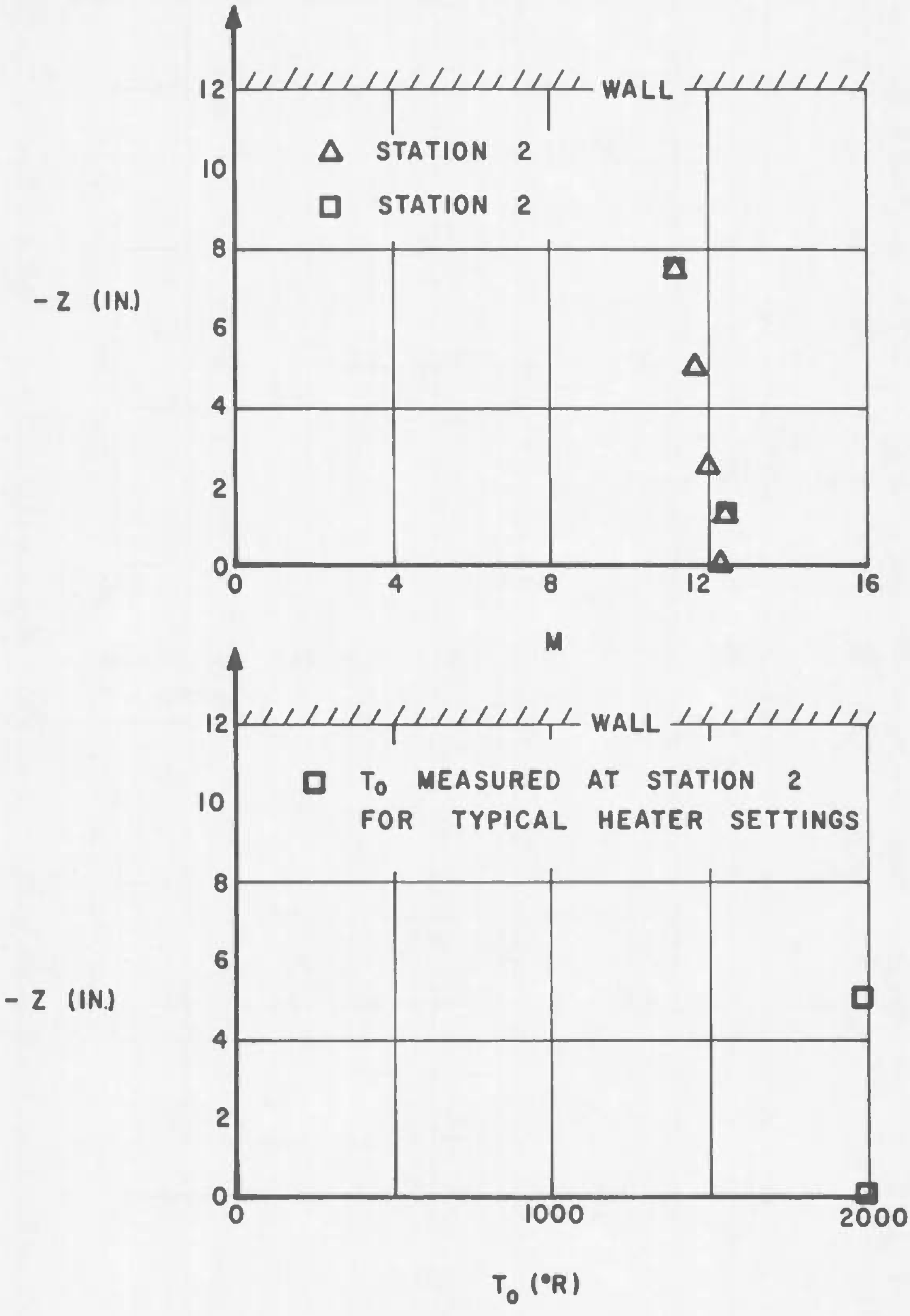


Fig. 11 T_0 and M at Station 2

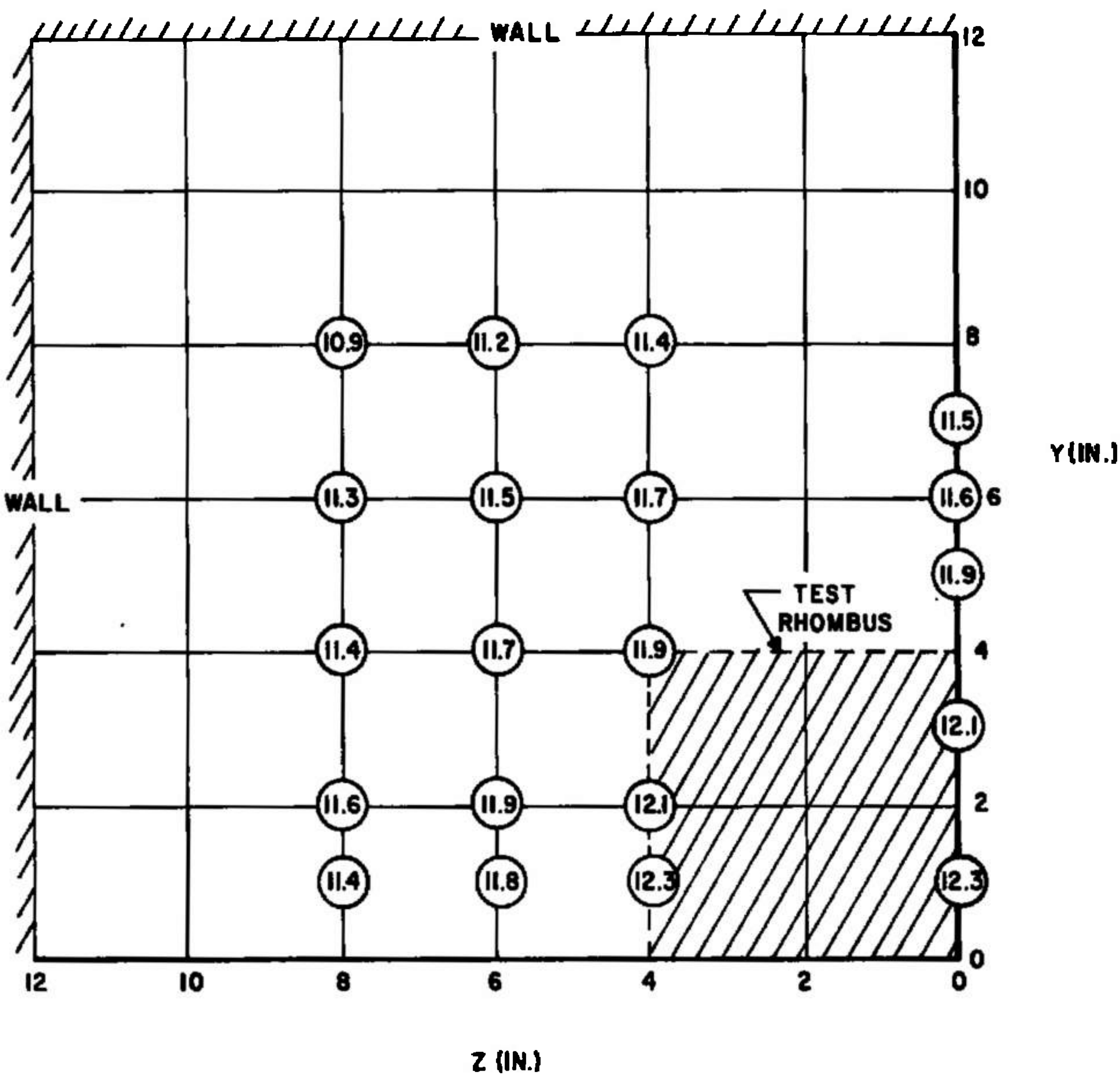


Fig. 12 Mach Number Distributions at Station 1

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13. ABSTRACT

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14. KEY WORDS	LINK A		LINK B		LINK C	
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nozzles						
hypersonic flow						
pressure						
temperature						

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